The balance functions in azimuthal angle is a measure of the transverse flow [★]

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Abstract

The charge or barion number balance function in the relative azimuthal angle of a pair of particles emitted in ultrarelativistic heavy ion collisions is studied. The $\pi^+\pi^-$ and $p\bar{p}$ balance functions are computed using thermal models with two different set of parameters, corresponding to a large freeze-out temperature and a moderate transverse flow or a small temperature and a large transverse flow. The single particle spectra including pions from resonance decays are similar for the two scenarios, on the other hand the azimuthal balance function is very different and could serve as an independent measure of the transverse flow at the freeze-out.

Key words: ultra-relativistic heavy-ion collisions, particle correlations, collective flow, freeze-out

The balance function in rapidity has been proposed as a measure of correlations between particles of opposite charges [1,2,3]. This includes the electric charge, the barion number or the strangeness, which we call below charge correlations, unless specified explicitly. Elementary processes occurring in heavy ion collisions conserve the charges which means that opposite charged particles are produced in pairs. One expects that due to such a microscopic local constraint on the production process of a pair of particles some correlations in the momenta of the particles appear.

We propose a new observable sensitive to the freeze-out characteristics, *the charge balance function in the relative azimuthal angle.* In the following we call this quantity the $\phi-$balance function, it is defined similarly to the charge balance function in rapidity

$$B^{\phi}(\delta\phi,\phi) = \frac{1}{2}\left\{\frac{\langle N_{+-}(\delta\phi,\phi)\rangle - \langle N_{++}(\delta\phi,\phi)\rangle}{\langle N_{+}(\phi)\rangle} \right.$$
$$\left. + \frac{\langle N_{-+}(\delta\phi,\phi)\rangle - \langle N_{--}(\delta\phi,\phi)\rangle}{\langle N_{-}(\phi)\rangle}\right\}, \tag{1}$$

where, e.g. the quantity $N_{+-}(\delta\phi,\phi)$ is defined as the number of pairs of particles with the particle $(+)$ flying at an angle ϕ and the particle $(-)$ at an angle $\phi + \delta\phi$. The dependence on the angle ϕ (measured with respect to the reaction plane) could be useful to study the difference between the correlations in and out of the reaction plane. Other quantities appearing in Eq. (1) are defined in an analogous way. In the following we study the azimuthally averaged $\phi-$balance function

$$B^{\phi}(\delta\phi) = \int\limits_{0}^{2\pi} d\phi B^{\phi}(\delta\phi,\phi) \tag{2}$$

and azimuthally symmetric freeze-out conditions. Obviously B^{ϕ} has the same normalization condition as the balance function in rapidity

$$\int\limits_{-\pi}^{\pi} d\delta\phi B^{\phi}(\delta\phi) = 1, \tag{3}$$

with the acceptance window and detector efficiency effects modifying the above relation [4,3]. The $\phi-$balance function can be studied in ultrarelativistic heavy ion experiments for different centrality and transverse momentum cuts.

The STAR Collaboration has presented results on the charge balance function for Au-Au collisions at RHIC, indicating a narrow correlation in rapidity [5,4], significantly smaller than observed in elementary particle collisions. It means that the charges in heavy ion collisions are produced in a different way than in elementary processes. In particular, this observation indicates the creation of charged particle pairs in the late stage of the collision.

Theoretical estimates of the balance function in rapidity for pion pairs have been obtained in the framework of thermal models [6,7]. The basic assumption behind those calculations is that the pair formation occurs in a thermalized local source. It is consistent with a late hadronization scenario, as the $\pi^{+}\pi^{-}$ pair must be created late in a system which undergoes a strong longitudinal flow [2]. The $\pi^{+}\pi^{-}$ balance function has two contributions, corresponding to two different mechanisms for the creation of a pair of opposite charges [6]. The first one (the resonance contribution) is determined by the decays of neutral hadronic resonances with a $\pi^{+}\pi^{-}$ pair in the final state. The second one (the nonresonant contribution) is given by the emission of pair of opposite charged

particles from a local thermal source. The momenta of the particles in the source rest frame are given by the thermal distribution, and are boosted by the velocity corresponding to the collective flow of the source. For the calculation of the $p\bar{p}$ correlation we take only the second mechanism, the emission from a thermal source.

We compare two different thermal models, the single freeze-out model [8] and the boost invariant blast-wave parameterization [9]. In the first case the kinetic freeze-out happens at the same time as the chemical one. The temperature of the latter is fixed by the observed particle ratios at a relatively high value of $T_f = 165$MeV. The elements of the hypersurface of emission are moving with a collective flow velocity given by the three dimensional Hubble flow. In the transverse direction the flow has the scaling form $\beta_r = \frac{r}{t}$ as a function of the radial distance r, with $t = \sqrt{\tau^2 + r^2}$, $\tau = 7.6$fm, and $0 < r < \rho = 6.7$fm. The parameters ρ and τ define the size of the source and the amount of the transverse flow. The average transverse velocity is $\langle \beta \rangle = 0.5$. On the other hand the blast wave model assumes a late kinetic freeze-out, happening some time after the chemical processes have ceased. The typical temperature at the freeze-out $T_f = 90$MeV and the parameters of the transverse flow are fixed by a fit to the transverse momentum spectra of pions, protons and kaons [9]. The transverse flow in the blast-wave parameterization is given by $\beta_r = \beta \left(\frac{r}{r_{max}} \right)^{\alpha}$ where the parameters $\alpha = 0.82$ and $\beta_r = 0.84$ are adjusted to describe the spectra in central events at $\sqrt{s} = 200$GeV. The freeze-out temperature and the flow profile depend on the energy and the centrality of the collision. In the following we take only the quoted above parameters of the blast-wave model corresponding to central events at the highest RHIC energy as representative for thermal models with a late kinetic freeze-out.

Both the single freeze-out model and the blast-wave model fit well the single -particle transverse momentum spectra. The reason is that in the first model a large freeze-out temperature is supplemented with a moderate flow $\langle \beta_r \rangle = 0.5$ and in the second model the emission at a small temperature happens in the presence of a significant transverse flow $\langle \beta_r \rangle = 0.6$. The resulting spectra of pions and protons are very similar (Fig. 1). Some difference is visible for low momentum pions but in the scenario with a high freeze-out temperature, most of the pions come from the decay of resonances. This effect modifies notice-ably the spectra at small momenta. The resulting transverse mass spectra for the single freeze-out model with resonance decays included is very similar to the blast wave results, although the temperatures are very different. Due to the combined effect of the transverse flow and of the thermal motion with the addition of resonance decays it is not possible to determine the freeze-out temperature and the flow from the spectra of light hadrons only. This lack of sensitivity is at the origin of two different parameterization of the freeze-out surface which can describe acceptably the experimental spectra of particles produced in ultrarelativistic heavy ion collisions. A simultaneous description
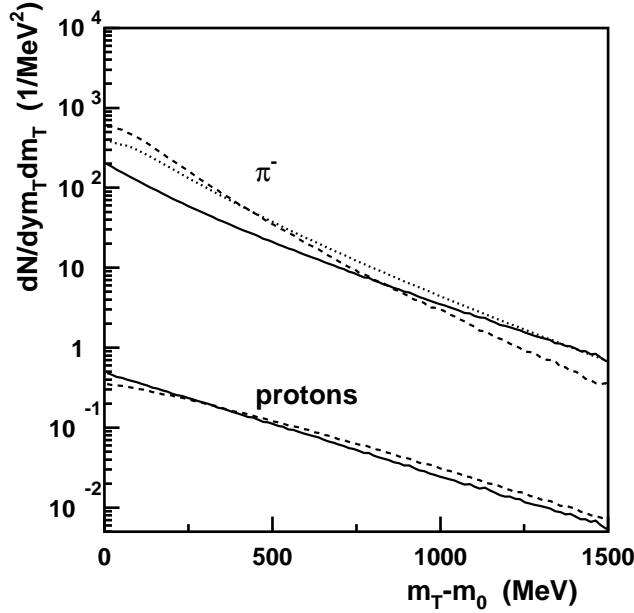
Fig. 1. Spectra in the transverse mass calculated in thermal models for two different freeze-out conditions. $T_f = 90\text{MeV}$ and $\langle\beta\rangle = 0.6$ (dashed line) and $T_f = 165\text{MeV}$ and $\langle\beta\rangle = 0.5$ (solid line) for pions (upper curves) and protons (lower curves). The dotted line denotes the pions obtained at the higher freeze-out temperature including pions from the decay of resonances. The normalization is arbitrary.

of HBT radii could give an additional constraint [10,11,12] but within both models the gross features of the observed correlation radii can be reproduced. From general principles different space-time emission function can given similar HBT correlations for on-shell pions.

In thermal models hadron production occurs at the chemical freeze-out. In the single freeze-out model [8] the kinetic and chemical freeze-outs happen at the same time and the distribution of momenta of a correlated pair of particles is not significantly changed after its creation. If the kinetic freeze-out is delayed, as in the blast-wave models, one has to assume that the two correlated particles are created in a local thermal ensemble at the chemical freeze-out and follow the same thermal history until the kinetic freeze-out. By rescattering the two particles stay in contact with the same local thermal system, as a consequence the particle momenta evolve with the decreasing temperature and increasing transverse flow of the system [7]. It has been noticed that the charge balance function in rapidity is somewhat sensitive to the characteristics of the final state [2,5,7]. For massive particles the width of the balance function decreases with increasing ratio of the mass to the temperature. The charge balance function in rapidity is narrower for pions emitted from a source with a large

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transverse velocity or for pions originating from the decay of a fast resonance [6,7]. The variation of the amount of transverse flow with the centrality of the collision can reproduce [7] the experimentally observed narrowing of the balance functions for central events [5]. The $\phi-$balance function measures the charge corelation in the relative angle of the emitted pair and not the rapidity. We show that this quantity is *very sensitive* to the characteristics of the freeze-out and could also give some insight into the microscopic process of the charge creation.

The calculation proceeds in a similar manner as for the charge balance function in rapidity [6]. For the $\pi^+\pi^-$ pairs we take explicitely into account the pion pairs from the decay of the neutral resonances

$$K_S, \ \rho^0, \ \sigma, \ \text{and} \ f_0, \tag{4}$$

as well pions emitted from the local thermal source. In the rest frame of the resonance, pions from a two-body decay are correlated back to back in the azimuthal angle. Nonresonant pion are emitted isotropically in the local frame of the source, therfore their correlation in the relative angle is flat. Isotropic emission is also a good approximation for the decays with many-body final states, therfore for the production of the resonant pion pairs we take into account only neutral resonances with two-body decays (4). The azimuthal angle correlations are modified by the collective flow of the thermal source or by the fact that the resonances decay in flight. In Fig. 2 is presented the $\phi-$balance function for pions from ρ decays (at $T_F = 165\text{MeV}$) and for nonresonant pions thermally emitted with the two freeze-out conditions that we consider. The contribution of pions from resonance decays can be neglected at $T_f = 90\text{MeV}$ and is not taken into account. Clearly, pions emitted with a small temperature have smaller relative momenta and after the boost from the rapidly moving source frame to the laboratory frame their momenta are pointing approximately in the same direction. The situation is different at the higher freeze-out temperature. First, thermally emitted pions have a significant thermal motion and second the boost to the laboratory frame is done with a smaller velocity. At $T_f = 165\text{MeV}$, 30% of pions [13] come from the decay of resonances (4). Due to the back to back emission the angular distribution of resonance decay products is even wider than for the nonresonant pions at $T_f = 165\text{MeV}$. It was noted that the effect of resonance decays reduces the elliptic flow of pions [14,10]. If restricted to $\pi^+\pi^-$ correlations and to the relative angle of the pair as for the $\phi-$balance function this effect is even stronger.

The correlation between the pions is given by a weigthed [6] sum of the two mechanisms (nonresonant pions and decay products of resonances listed in (4)) for $T_f = 165\text{MeV}$ and by nonresonant pion pairs for the freeze-out at 90MeV. The width of resulting $\phi-$balance function is very different (Fig. 3). At $T_f = 165\text{MeV}$ both the nonresonant pion pairs and pion pairs from the
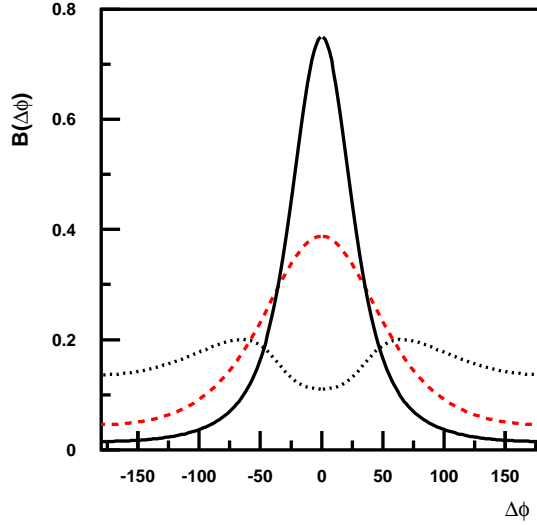
Fig. 2. Balance functions for pions in thermal models calculated for two different freeze-out conditions : $T_f = 165\text{MeV}$, $\langle\beta\rangle = 0.5$ (dashed line for nonresonant pions and dotted line for pions from the decay of a ρ_0 resonance) and for nonresonant pions at $T_f = 90\text{MeV}$, $\langle\beta\rangle = 0.6$ (solid line).

decay of resonances have a large angular separation. The contribution of the resonant pion pairs makes the $\phi-$balance function show a flat correlation between $-50°$ and $50°$. The width of the $\phi-$balance function decreases with the mean transverse momentum of the pion pair. The average angle between a π^+ and a π^- is $54°$ for pairs of 1GeV total transverse momentum and $24°$ for the total momentum of 2GeV if the pions are emitted at $T_f = 90\text{MeV}$, whereas it is $80°$ and $50°$ respectively for pions emitted at the higher freeze-out temperature. Of course for very small total momentum of the pair the correlation is trivially dominated by back to back emission. Changing the mean momentum of the pair the contribution of pions from resonance decays changes, being the largest for small momenta.

In Fig. 4 the $\phi-$balance function for protons and antiprotons is shown. Very similar behavior appears as for the pion correlations. The emission at higher temperature and smaller transverse flow produces proton and antiproton pairs less focused in the azimuthal angle. Protons which are quite massive are more sensitive to the transverse flow and have less thermal motion than pions. Also resonance decays are expected not to modify significantly our estimates for the baryonic charge $\phi-$balance function; fits to the experimental data could give direct information on the freeze-out parameters.
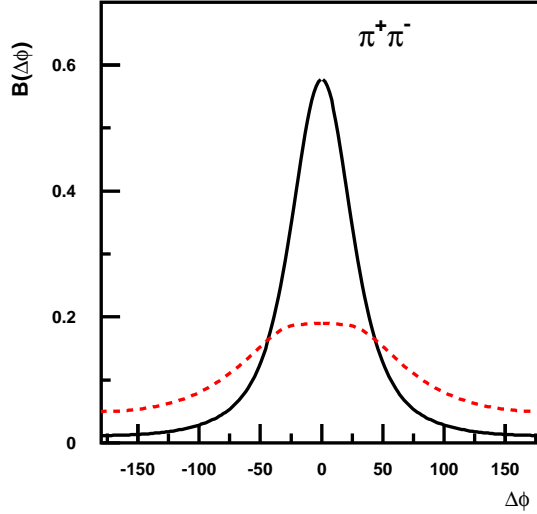
Fig. 3. Balance functions for pions in thermal models calculated for two different freeze-out conditions : $T_f = 165\text{MeV}$, $\langle\beta\rangle = 0.5$ (dashed line) and $T_f = 90\text{MeV}$, $\langle\beta\rangle = 0.6$ (solid line).

In summary, we propose to study charge-anticharge correlations *in the azimuthal angle*. The experimental observable is defined as the charge balance function in the relative azimuthal angle of the particle pair. The measurement of the $\phi-$balance function in heavy ion collisions could serve as another independent constraint on the temperature and the amount of the transverse flow at the freeze-out. The effect of an increase of the freeze-out temperature and of a simultaneous decrease of the transverse flow compensate to a large extend in the single particle spectra. On the other hand both the increase of the temperature and the reduction of the transverse flow make the $\phi-$balance function wider. Accordingly the width of the $\phi-$balance function could be used independently of the particle spectra and HBT radii to determine the values of the freeze-out parameters. Explicit estimates of the $\phi-$balance function for two thermal models with different freeze-out temperatures and different transverse flow confirm these expectations both for $\pi^+\pi^-$ and $p\bar{p}$ pairs. We find that the most sensitive region is for the total momentum of the pair of around 1GeV.

Finally we note that the $\phi-$balance function $B^\phi(\delta\phi, \phi)$ with angular dependence with respect to the reaction plane (Eq. 1) could give some insight into the angular dependence of the transverse flow. The elliptic flow gives a combined information on the spatial and momentum asymmetries [10,12]. The measurement of the angular dependence of the width of the $\phi-$balance func-
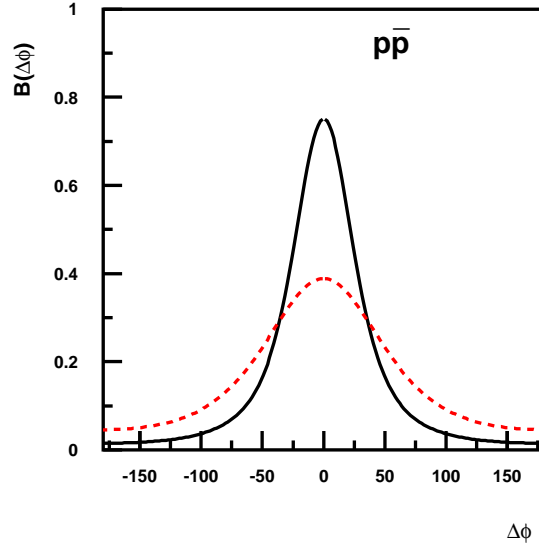
Fig. 4. Proton-antiproton balance functions in thermal models calculated for two different freeze-out conditions, as in Fig. 3.

tion could serve as a probe of the momentum asymmetry alone.

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